Recent theoretical progress in hypernuclear decay

G. Garbarino

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DECAY MODES OF Λ–HYPERNUCLEI

MESONIC

$$\Lambda \rightarrow \pi^0 n \qquad \Gamma_{\pi^0} \qquad p_N \simeq 100\,\mathrm{MeV} << k_F^0 \simeq 270\,\mathrm{MeV}$$

$$\Lambda \rightarrow \pi^- p \qquad \Gamma_{\pi^-}$$

NON–MESONIC

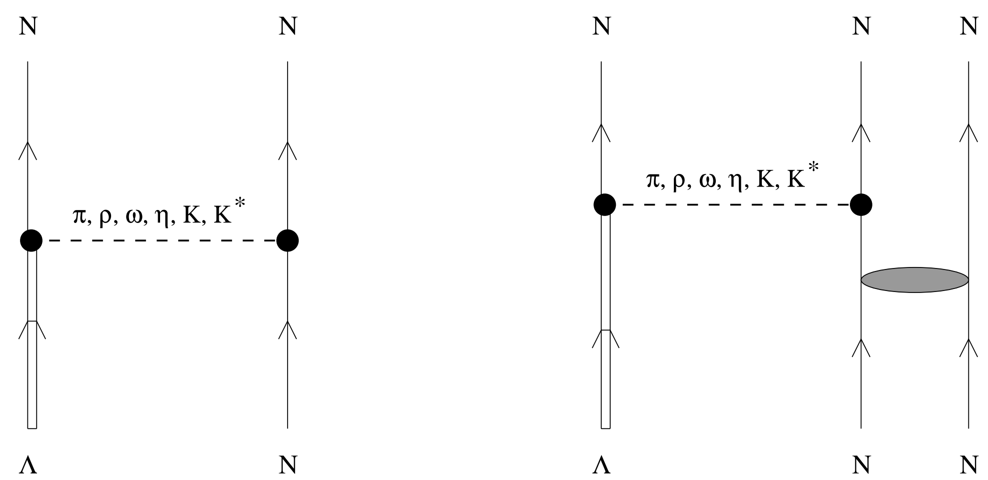
One–nucleon induced

$$\Lambda n \rightarrow nn \qquad \Gamma_n \qquad p_N \simeq 410\,\mathrm{MeV}$$

$$\Lambda p \rightarrow np \qquad \Gamma_p$$

Two–nucleon induced

$$\Lambda NN \rightarrow nNN \qquad \Gamma_2 \qquad p_N \simeq 330\,\mathrm{MeV}$$



$$\Gamma_{\mathrm{T}} = \Gamma_{\mathrm{M}} + \Gamma_{\mathrm{NM}} = \Gamma_{\pi^0} + \Gamma_{\pi^-} + \Gamma_n + \Gamma_p + \Gamma_2$$

THE Γ_n/Γ_p PUZZLE

For many years, a sound theoretical explanation of the large experimental values of Γ_n/Γ_p has been missing.

Theory strongly underestimated Γ_n/Γ_p data

[W. M. Alberico and G. Garbarino, Phys. Rept. 369, 1 (2002)]

For ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C:

$$\left[\frac{\Gamma_n}{\Gamma_p}\right]^{\rm Th} \simeq 0.1 \div 0.5 \ll \left[\frac{\Gamma_n}{\Gamma_p}\right]^{\rm Exp} \simeq (1 \div 2) \pm 1$$

Experiment

- Until recently, large uncertainties in the extraction of the ratio from data: only single–proton spectra measured, very indirect determination of decay rates, probable overestimation of Γ_n/Γ_p
- KEK: simultaneous measurement of single–proton and single–neutron spectra, improved determination from N_n/N_p ratio
- KEK: nucleon–nucleon coincidence spectra, more direct determination from N_{nn}/N_{np} ratio
- Forthcoming data from FINUDA, experiments planned at HypHI and J–PARC

Theory

The One–Pion–Exchange (OPE) model predicts very small ratios for ${}^{5}_{\Lambda}\mathrm{He}$ and ${}^{12}_{\Lambda}\mathrm{C}$:

$$\left[\frac{\Gamma_n}{\Gamma_p}\right]^{\rm OPE} = 0.1 \div 0.2$$

but reproduces the observed total non–mesonic rates, $\Gamma_{\rm NM} = \Gamma_n + \Gamma_p (+\Gamma_2)$.

Other interaction mechanisms beyond the OPE should then be responsible for the overestimation of Γ_p and the underestimation of Γ_n

- heavier mesons (ρ, K, K^*, ω, η, $2\pi/\rho$, $2\pi/\sigma$) [Parreño et al., Itonaga et al., Jido et al.,]
- direct quark mechanism [Oka et al.]
- two–nucleon induced mechanism [Alberico et al., Ramos et al.]
- nucleon final state interactions [Garbarino et al.]

A few calculations with $\Lambda N \to nN$ transition potentials including heavy meson exchange [1] and/or direct quark contributions [2] have recently improved the situation ($\Gamma_n/\Gamma_p \simeq 0.3 \div 0.5$), without providing an explanation of the origin of the puzzle

[1] D. Jido, E. Oset and J. E. Palomar, NPA 694, 525 (2001);
A. Parreño and A. Ramos, PRC 65, 015204 (2002);
K. Itonaga, T. Ueda and T. Motoba, PRC 65, 034617 (2002).

[2] K. Sasaki, T. Inoue and M. Oka, NPA 669, 331 (2000); A 678 455E (2000).

In addition, determinations of Γ_n/Γ_p from data required [3]:

- the inclusion of the TWO–NUCLEON INDUCED DECAY MECHANISM, $\Lambda NN \to nNN$, whose experimental identification is expected in NNN coincidence measurements (FINUDA, HypHI, J–PARC, KEK)
- the evaluation of the NUCLEON FSI INSIDE THE RESIDUAL NUCLEUS AND IN THE EXPERIMENTAL SET–UP

[3] G. Garbarino, A. Parreño, A. Ramos, PRL 91, 112501 (2003); PRC 69, 054603 (2004)

+ KEK nucleon coincidence data $\Rightarrow \Gamma_n/\Gamma_p \simeq 0.3 \div 0.4$

convincing evidence for a SOLUTION OF THE PUZZLE

THE ASYMMETRY PUZZLE

Non–Mesonic Weak Decay of Polarized Λ–hypernuclei

Weak decay proton intensity from $\vec{\Lambda} p \to np$

$$I(\Theta) = I_0\,[1 + p_\Lambda\, a_\Lambda \cos\Theta]$$

$$\begin{aligned} p_\Lambda &= \Lambda\,\text{polarization} \\ a_\Lambda &= \text{intrinsic } \Lambda \text{ asymmetry parameter} \end{aligned}$$

Nucleon FSI modify the weak decay proton intensity $I(\Theta)$. Experiments measure

$$I^{\rm M}(\Theta) = I_0^{\rm M}\,[1 + p_\Lambda\, a_\Lambda^{\rm M} \cos\Theta]$$

then the observable asymmetry $a_\Lambda^{\rm M}$ is determined as:

$$a_\Lambda^{\rm M} = \frac{1}{p_\Lambda} \frac{I^{\rm M}(0^\circ) - I^{\rm M}(180^\circ)}{I^{\rm M}(0^\circ) + I^{\rm M}(180^\circ)}$$

by using an indirect measurement (${}^{5}_{\Lambda}$He) or a theoretical evaluation (${}^{12}_{\Lambda}$C) of p_Λ.

	$^{5}_{\Lambda}$He	$^{12}_{\Lambda}$C
Sasaki et al. a_{Λ}		
$\pi + K + \mathrm{DQ}$	-0.68	
Parreño et al.		
$\pi + \rho + K + K^* + \omega + \eta$	-0.68	-0.73
Itonaga et al.		
$\pi + K + 2\pi/\rho + 2\pi/\sigma + \omega$	-0.33	
Barbero et al.		
$\pi + \rho + K + K^* + \omega + \eta$	-0.54	-0.53
KEK–E160 a_{Λ}^{M}		-0.9 ± 0.3
KEK–E278	0.24 ± 0.22	
KEK–E508 (prel.)		-0.44 ± 0.32
KEK–E462	$0.11 \pm 0.08 \pm 0.04$	

KEK–E160: S. Ajimura et al., Phys. Lett. **B 282**, 293 (1992)
KEK–E278: S. Ajimura et al., Phys. Rev. Lett. **84**, 4052 (2000)
KEK–E508: T. Maruta et al., Nucl. Phys. **A 754**, 168 (2005)
KEK–E462: T. Maruta et al., nucl-exp/0509016

FSI prevent establishing direct comparisons between a_{Λ} and a_{Λ}^{M}. A theoretical evaluation of a_{Λ}^{M} is thus required.

OUR APPROACH

[PRL 91, 112501 (2003); PRC 69, 054603 (2004); PRL 94, 082501 (2005)]

Study of the NUCLEON DISTRIBUTIONS in the NMWD of ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C hypernuclei

- SINGLE NUCLEON ENERGY SPECTRA
- NN ANGULAR AND ENERGY CORRELATION SPECTRA
- PROTON INTENSITIES FROM POLARIZED HYPERNUCLEI

$\Longrightarrow$ determine Γ_n/Γ_p and a_Λ

via the comparison with observed distributions

- Finite Nucleus treatment for $\Lambda N \to nN$ (OME $= \pi + \rho + K + K^* + \omega + \eta$)

  [A. Parreño, A. Ramos and C. Bennhold, PRC 56 (1997) 339; A. Parreño and A. Ramos, PRC 65 (2002) 015204]

- Polarization Propagator method in LDA for $\Lambda NN \to nNN$ (correlated OPE)

  [W.M. Alberico, A. De Pace, G. Garbarino and A. Ramos, PRC 61 (2000) 044314]

- Intranuclear Cascade calculation

  [A. Ramos, M. J. Vicente-Vacas and E. Oset, PRC 55 (1997) 735; C 66 (2002) 039903(E)]

RESULTS

Γ_n/Γ_p

Number of primary nn and np pairs:

$$N_{nn}^{\rm wd} \propto \Gamma_n$$
$$N_{np}^{\rm wd} \propto \Gamma_p$$

Denoting with N_{nn} and N_{np} the number of nucleons emitted by the nucleus:

$$\boxed{\frac{\Gamma_n}{\Gamma_p} \equiv \frac{N_{nn}^{\rm wd}}{N_{np}^{\rm wd}} \neq \frac{N_{nn}}{N_{np}} = R_2\,(\Delta\theta_{12}, \Delta T_N, \Gamma_2, {\rm FSI})}$$

Table 1: N_{nn}/N_{np} for ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C ($\cos\theta_{NN} \leq -0.8$ and $T_N^{\rm th} = 30$ MeV)

	${}^{5}_{\Lambda}$He N_{nn}/N_{np}	${}^{5}_{\Lambda}$He Γ_n/Γ_p	${}^{12}_{\Lambda}$C N_{nn}/N_{np}	${}^{12}_{\Lambda}$C Γ_n/Γ_p
OPE	0.25	0.09	0.24	0.08
OME	0.51	0.34	0.39	0.29
KEK–E462	$0.45 \pm 0.11 \pm 0.03$			
KEK–E508 (prel.)			0.40 ± 0.09	

Data from B. H. Kang et al., nucl-ex/0509015; H. Outa, NPA 754, 157c (2005)

A weak–decay–model independent analysis of Γ_n/Γ_p

- Total number of NN pairs emitted per NMWD:

$$
\begin{aligned}
N_{nn} &= \frac{N^{\rm 1Bn}_{nn}\,\Gamma_n + N^{\rm 1Bp}_{nn}\,\Gamma_p + N^{\rm 2B}_{nn}\,\Gamma_2}{\Gamma_n + \Gamma_p + \Gamma_2} \\
N_{np} &= \frac{N^{\rm 1Bn}_{np}\,\Gamma_n + N^{\rm 1Bp}_{np}\,\Gamma_p + N^{\rm 2B}_{np}\,\Gamma_2}{\Gamma_n + \Gamma_p + \Gamma_2}
\end{aligned}
$$

  which define the six weak–decay–model independent quantities: $N^{\rm 1Bn}_{nn}$ (the number of nn pairs emitted per neutron–induced NMWD), etc.

- From a measurement of N_{nn}/N_{np} and appropriate values for Γ_2/Γ_1:

$$
\frac{\Gamma_n}{\Gamma_p} = \frac{N^{\rm 1Bp}_{nn} + N^{\rm 2B}_{nn}\dfrac{\Gamma_2}{\Gamma_1} - \left(N^{\rm 1Bp}_{np} + N^{\rm 2B}_{np}\dfrac{\Gamma_2}{\Gamma_1}\right)\dfrac{N_{nn}}{N_{np}}}{\left(N^{\rm 1Bn}_{np} + N^{\rm 2B}_{np}\dfrac{\Gamma_2}{\Gamma_1}\right)\dfrac{N_{nn}}{N_{np}} - N^{\rm 1Bn}_{nn} - N^{\rm 2B}_{nn}\dfrac{\Gamma_2}{\Gamma_1}}
$$

- From KEK data we obtained:

${}^{5}_{\Lambda}$He	$\Gamma_n/\Gamma_p = 0.27 \pm 0.11$	$\Gamma_2 = 0.20\,\Gamma_1$	$(\Gamma_n/\Gamma_p = 0.40 \pm 0.11 \quad \Gamma_2 = 0)$
${}^{12}_{\Lambda}$C	$\Gamma_n/\Gamma_p = 0.29 \pm 0.14$	$\Gamma_2 = 0.25\,\Gamma_1$	$(\Gamma_n/\Gamma_p = 0.38 \pm 0.14 \quad \Gamma_2 = 0)$

We are now studying in more detail the two–nucleon induced decay channel

- more microscopic (i.e., less phenomenological)
- $\Lambda nn \to nnn$ and $\Lambda pp \to npp$ also included in addition to $\Lambda np \to nnp$
- $\Gamma_{nn} = \Gamma(\Lambda nn \to nnn) \quad \Gamma_{np} = \Gamma(\Lambda np \to nnp) \quad \Gamma_{pp} = \Gamma(\Lambda pp \to npp)$
- $\Gamma_2 = \Gamma_{nn} + \Gamma_{np} + \Gamma_{pp}$
- For ${}^{12}_{\Lambda}\mathrm{C}$: $\Gamma_2/\Gamma_1 = 0.26 \quad \Gamma_{np}/\Gamma_1 = 0.20 \quad \Gamma_{pp}/\Gamma_1 = 0.05 \quad \Gamma_{nn}/\Gamma_1 = 0.01$
- A preliminary analysis or KEK nucleon–nucleon correlation spectra confirm the previous determination: $\boxed{\frac{\Gamma_n}{\Gamma_p}({}^{12}_{\Lambda}\mathrm{C}) = 0.3 \pm 0.1}$

ASYMMETRY

The calculated proton intensities turn out to be well fitted by

$$I^{\mathrm{M}}(\Theta) = I_0^{\mathrm{M}} \left[1 + p_\Lambda \, a_\Lambda^{\mathrm{M}} \cos\Theta\right]$$

thus a_Λ^{M} can be obtained as:

$$a_\Lambda^{\mathrm{M}} = \frac{1}{p_\Lambda} \frac{I^{\mathrm{M}}(0^\circ) - I^{\mathrm{M}}(180^\circ)}{I^{\mathrm{M}}(0^\circ) + I^{\mathrm{M}}(180^\circ)}$$

Table 2: OME asymmetry parameters for ${}^{5}_{\Lambda}\mathrm{He}$, ${}^{11}_{\Lambda}\mathrm{B}$ and ${}^{12}_{\Lambda}\mathrm{C}$

	${}^{5}_{\Lambda}\mathrm{He}$	${}^{11}_{\Lambda}\mathrm{B}$	${}^{12}_{\Lambda}\mathrm{C}$
a_Λ	-0.68	-0.81	-0.73
$a_\Lambda^{\mathrm{M}}(T_p^{\mathrm{Th}} = 30\ \mathrm{MeV})$	-0.46	-0.39	-0.37
$a_\Lambda^{\mathrm{M}}(T_p^{\mathrm{Th}} = 50\ \mathrm{MeV})$	-0.52	-0.55	-0.51
$a_\Lambda^{\mathrm{M}}(T_p^{\mathrm{Th}} = 70\ \mathrm{MeV})$	-0.55	-0.70	-0.65
KEK–E462	$0.11 \pm 0.08 \pm 0.04$		
KEK–E508 (prel.)		0.11 ± 0.44	-0.44 ± 0.32

Data from T. Maruta et al., nucl-ex/0509016; NPA 754, 168c (2005)

CONCLUSIONS

✦ Weak–decay–model independent analysis of $^5_\Lambda$He and $^{12}_\Lambda$C KEK coincidence data:

$$\boxed{\Gamma_n/\Gamma_p \simeq (0.3 \div 0.4) \pm 0.1}$$

in agreement with pure theoretical calculations

$\Longrightarrow$ SOLUTION OF THE Γ_n/Γ_p PUZZLE

Forthcoming coincidence data from FINUDA, HypHI, J–PARC and KEK for better determinations of Γ_n/Γ_p and first constraints on Γ_2/Γ_1

✦ The ASYMMETRY PUZZLE REMAINS UNSOLVED. Not even analyses including nucleon FSI, which turn out to be very important in hypernuclear NMWD, can account for the present asymmetry data

THEORY predicts negative asymmetry values, moderately dependent on the hypernucleus, EXPERIMENT favors $a_\Lambda^{\rm M}(^{12}_\Lambda{\rm C}) < 0$ but $a_\Lambda^{\rm M}(^5_\Lambda{\rm He}) \gtrsim 0$

Theoretically, apart from recent claims [Parreño at al., Oka et al., Barbero et al.] on the possible relevance of the σ–meson–exchange, there seems to be no other reaction mechanism which may be responsible for $a_\Lambda^{\rm M} \gtrsim 0$

Experimentally, the present anomalous discrepancies among data for different hypernuclei need to be resolved $\Longrightarrow$ new and/or improved experiments (inverse reaction $\vec{p}n \to p\Lambda$ as well) are required